Using Single-Cycle Magellan Radar Imagery to Constrain Heights and Slope Angles of Venusian Geologic Features.
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Introduction. The three-dimensional geometry (planform and vertical components) of many geologic surface features on Venus constrains interpretations of their structural style and origin. Radar images returned via the Magellan mission provide representations of the planform, or horizontal geometry, albeit with possible imaging and processing artifacts or distortions, of nearly 98% of the Venusian surface. Horizontal resolution (~100-250 m at full resolution) is sufficient to resolve the planform characteristics of many individual features, *e.g.*, faults, folds, craters, and volcanic edifices. However, determining their vertical relief proves more difficult. The large "footprint" of the Magellan altimeter instrument, and thus the comparatively low resolution of the altimetry data (several km), disallows accurate vertical relief determinations for most individual structures. Radargrammetric calculations, however, by measuring planform distortions provide an alternate approach for determining vertical relief, and therefore heights, depths, and slope angles. This paper provides methodology for using *single* radar images to determine relief of several types of geologic features.

Radargrammetry. Locations of image pixels are derived from two factors [1]: (1) across-track distance or range, the distance from antenna to imaged features, is determined by the time delay of an echo pulse, whereas (2) along-track position is based on the expected Doppler shift of a returned pulse from a given terrain. The transformation of radar echoes to image pixels is based on assumptions of the long-wavelength shape (100s of km) of the imaged surface. Smaller-scale variants to this assumed shape, particularly changes in local topography, however, affect the location of pixels, resulting in geometric distortions of imaged features. Because high areas are closer to the spacecraft than surrounding areas, they return an echo sooner, and as a result high areas in the processed image are shifted or displaced opposite the radar look direction, or toward the spacecraft. Low areas return echoes slower, and are shifted in the look direction, away from the spacecraft. Thus, high features are foreshortened, whereas low features are elongated. Layover represents extreme foreshortening, whereby an echo pulse from a mountain top apparently overlies or is superimposed on the valley bottom, and possibly onto the next ridge flank as well. Thus, although the radar signals are processed to a flat, two-dimensional image, radar image distortions from foreshortening and elongation preserve information regarding the third, vertical dimension.

Heights are typically determined by comparing distortions of the same feature on stereoscopic radar images, two images with different incident angles and with either same-side or opposite-side look directions [see, *e.g.*, 1-2]. Unfortunately, nearly 50% of the Venusian surface was imaged by only one data cycle [3-4], thereby limiting stereo analysis. However, in certain situations, a single radar image can be used to determine heights, thus allowing relief determinations in areas with only single-cycle coverage. Three key factors are necessary for such analysis: (1) presence of oppositely-dipping slopes, as reflected by "paired" radar-bright and -dark slopes, (2) symmetry, *i.e*., the same dip angle for both slopes, and (3) equal relief of both slopes above or below a horizontal datum. Several different geologic features potentially satisfy these three constraints (Fig. 1). Embayment by volcanic flood lava flows provides a good datum plane, assuming no subsequent tilting, but feature heights will be underestimated. Even if it proves difficult to ascertain whether each constraint is satisfied, assuming these conditions provides a starting point for relief determinations, from which estimation curves can be developed by varying each constraint (*e.g.*, by assuming different asymmetries to determine how that affects calculated heights and slope angles).

Equations for determining feature heights from single radar images are case specific, limited to specific radar conditions. Previously, [5] calculated the depth and slopes of Yablochkina crater by measuring distortions of oppositely-dipping crater walls, but, as she noted, her equations are applicable only if radar layover is absent. For completeness, I provide here derivations of height and slope angle for examples without layover (Fig. 2), as based on [5], and new derivations for examples with layover (Fig. 3). Required data inputs are incidence angle θ_i ([1,3] provide tables relating θ_i to latitude and cycle number); and the ground range widths of the radar-bright and -dark slopes as measured parallel to radar illumination direction, respectively, g_{bs} and g_{ds}. The height h and apparent slope angle φ_a can then be determined using either Figure 2 or 3, depending upon absence or presence of layover. Layover effects, if present, are typically readily observable on the radar images (antiformal ridge crests superimposed onto adjacent synformal valleys, as at Akna Montes, Ishtar Terra, represents an obvious example). The calculated slope angle is an apparent angle because radar illumination direction typically does not correspond to the actual slope direction (generally perpendicular to slope trend), but the true maximum slope angle φ_t can be determined from the classical equation $\varphi_t = \text{atn} [\tan \varphi_a / \cos \Delta azim]$, where $\Delta azim$ is the change in azimuth between the actual slope direction and the radar illumination direction. Furthermore, in the case where slopes are not homoclinal, but rather curved (for example, as in folds), the calculated slope angles represent an average.

Discussion and Summary. Caution must be exercised during single-cycle radargrammetric analysis, and failure to do so may result in erroneous results. For example, a suitable volcanic cone should exhibit a circular shape, because if the "base level" is horizontal, the base of the cone will not be modified by radar foreshortening or elongation (these factors result from changes in relief; a horizontal base therefore remains unchanged); an elliptical base likely represents either a tilted base level (therefore failing constraint 3 above), or modification by wind (thus potentially failing constraint 2; see, *e.g.*, Figs. 5a and 20b of [6]). If the base level exhibits tilting, more complex formulas can be derived to "remove" the effects of tilting. As another example, impact craters may exhibit complexities from the simplified depiction in Fig. 1f—oblique impactors typically form steeper slopes for the uprange wall versus the downrange wall [*e.g.*, 7], thus failing constraint 3 and likely constraint 2 as well, but because craters formed by oblique impact typically exhibit bilateral symmetry about the impact trajectory line, the walls facing perpendicular to that line likely represent the best slopes for radargrammetric analysis. Curved slopes also pose potential problems, in that the portion of the slope first imaged, and thus processed on the ground range image as the closest part to the radar instrument, may not be the top or the bottom of the slope but rather some midslope point, which may affect ground range measurements and thus calculated heights and slope angles. Layover also results in some peculiar effects; in particular, the radar-facing (and thus bright) slope is imaged from top to bottom, and thus the processed ground range image shows that slope reversed from what might be expected, with its bottom juxtaposed against a midslope position of the opposite-facing, radar-dark slope (compare Figs. 2 and 3). These comments represent but a few of the potential problems that may affect radargrammetric analysis, but awareness of potential problems, perhaps by forward-modeling experiments (*i.e.*, creating synthetic radar depictions of specific geometries), may indicate feasibility or lack thereof of radargrammetric analysis.

Because the vertical dimension represents a fundamental constraint on geologic interpretations, and because many individual geologic features are below the altimeter instrument resolution, radargrammetry represents a major tool for geologic investigations of Venus's surface. Stereoscopic data represent the best case scenario because limiting constraints imposed by single-cycle analysis do not apply, but unfortunately stereoscopic data is limited in availability. Single-cycle approaches thus represent a possible way to glean valuable vertical relief data from areas without stereo coverage. For example, [8] used the techniques presented herein to determine heights and slope angles of paired radar-dark and -bright lineaments in southwestern Fortuna Tessera, confirming earlier analyses by [9] that the lineaments exhibited relatively low relief with nearly vertical slopes—the constraints provided by radargrammetric analysis, in concert with other constraints, favored an open fracture model over a normal-faulted graben model; thus, radargrammetry provided a key tool for distinguishing between these two structural models.

References Cited. [1] Plaut, J.J. (1993), *JPL Publ*. **93-24**, 33; [2] Conners, C. (1995), *JGR* **100**, 14361; [3] Saunders, R.S., *et al*. (1992), *JGR* **97**, 13067; [4] Ford, J.P. (1993), *JPL Publ*. **93-24**, 1; [5] Weitz, C.M. (1993), *JPL Publ*. **93-24**, 75; [6] Greeley, R. (1992), *JGR* **97**, 13319; [7] Schultz, P.H. (1992), *JGR* **97**, 16183; [8] Hansen, V.L., and J.J. Willis (1996), *Icarus* **123**, 296; [9] Hansen, V.L., and J.J. Willis (1997), this volume.

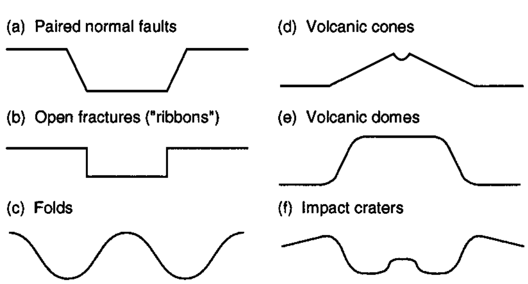

Figure 1. Possible geologic features satisfying constraints imposed by single-cycle radargrammetry, namely opposite-dipping slopes, symmetry, and equal relief.

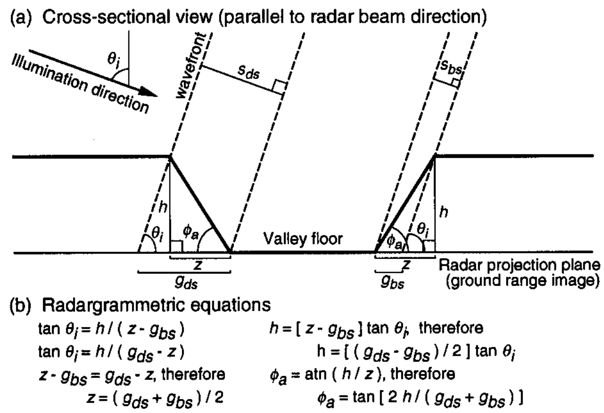

Figure 2. Radargrammetric relations of symmetric, opposite-dipping slopes of equal relief, where layover is not a factor. Derivations can be used for all examples in Fig. 1. s_{bs} and s_{ds}, slant range widths of radar-dark and -bright slopes, respectively; g_{bs} and g_{ds}, ground range widths of the bright and dark slopes, respectively, as measured parallel to the radar illumination direction; z, actual horizontal width (without distortion) of scarps as measured parallel to the beam direction; θ_i, incidence angle; φ_a, apparent slope angle; h, height of geologic feature.

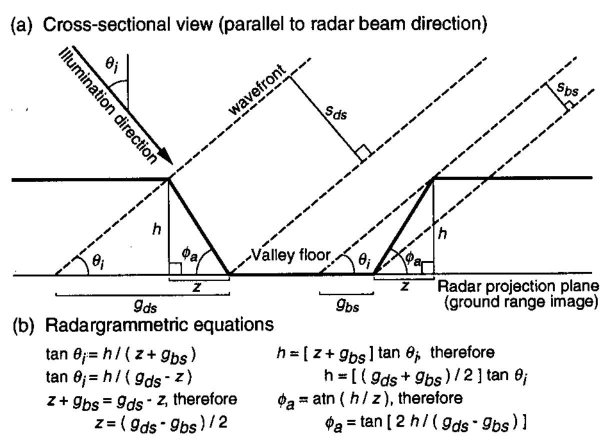

Figure 3. Radargrammetric relations of symmetric, opposite-dipping slopes of equal relief, with layover.